Properties of stellar matter in supernova explosions and nuclear multifragmentation

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During the collapse of massive stars, and the supernova type-II explosions, stellar matter reaches densities and temperatures which are similar to the ones obtained in intermediate-energy nucleus-nucleus collisions. The nuclear multifragmentation reactions can be used for determination of properties of nuclear matter at subnuclear densities, in the region of the nuclear liquid-gas phase transition. It is demonstrated that the modified properties of hot nuclei (in particular, their symmetry energy) extracted from the multifragmentation data can essentially influence nuclear composition of stellar matter. The effects on weak processes, and on the nucleosynthesis are also discussed.

1. INTRODUCTION

One of the most spectacular events in astrophysics is the type II supernova explosion which releases of about 10^{53} erg of energy, or several tens of MeV per nucleon [1]. When the core of a massive star collapses, it reaches densities several times larger than the normal nuclear density $\rho_0 \approx 0.15$ fm^{-3}. The repulsive nucleon-nucleon interaction gives rise to a bounce-off and creation of a shock wave propagating through the in-falling stellar material. This shock wave is responsible for the ejection of a star envelope that is observed as a supernova explosion. During the collapse and subsequent explosion the temperatures $T \approx (0.5 \div 10)$ MeV and baryon densities $\rho \approx (10^{-5} \div 2)\rho_0$ can be reached. As shown by many theoretical studies, a liquid-gas phase transition is expected in nuclear matter under these conditions. It is remarkable that similar conditions can be obtained in energetic nuclear collisions in terrestrial laboratories, which lead to multifragmentation reactions.

Multifragmentation, i.e. a break-up of nuclei into many small fragments, has been observed in nearly all types of nuclear reactions when a large amount of energy is deposited in nuclei. It includes reactions induced by protons, pions, antiprotons, and by heavy ions of both, relativistic energies (peripheral collisions) and 'Fermi'-energies (central collisions) [2, 3,4,5,6,7,8,9]. According to the present understanding, multifragmentation is a relatively fast process, with a characteristic time around 100 fm/c, where, nevertheless, a high degree of equilibration is reached. The process is mainly associated with abundant production of intermediate mass fragments (IMFs, with charges $Z \approx$ 3-20). However, at the onset of multifragmentation, also heavy residues are produced which have previously only been associated with compound-nucleus processes. At very high excitation energies, the IMF production gives way to the total vaporization of nuclei into nucleons and very light clusters.

2. PHASE DIAGRAM OF NUCLEAR MATTER

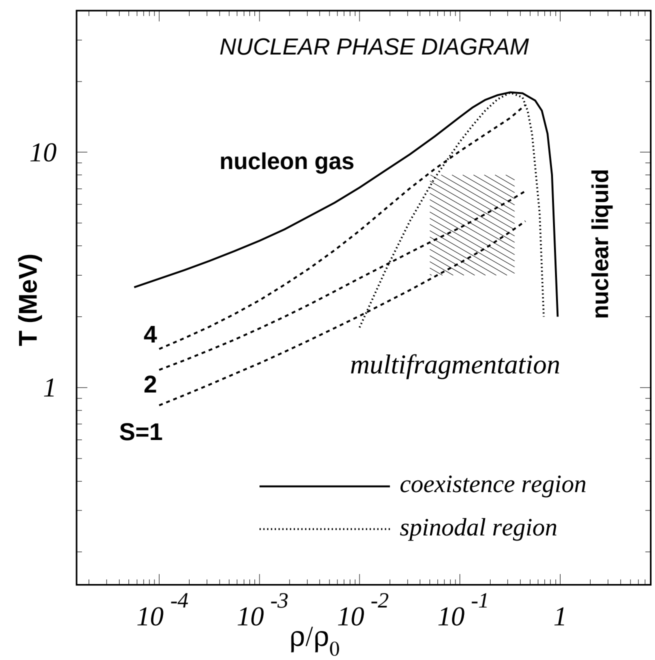

Figure 1. Nuclear phase diagram on the temperature–density plane. Solid and dotted lines give borders of the liquid-gas coexistence region and the spinodal region. The shaded area corresponds to conditions reached in nuclear multifragmentation reactions. The dashed lines are isentropic trajectories characterized by constant entropies per baryon (S =1, 2, and 4).

The multifragmentation reaction can be considered as an experimental tool to study the properties of hot fragments and the phase diagram of nuclear matter at densities $\rho \sim 0.1\rho_0$ and temperatures around $T \approx$ 3–8 MeV which are expected to be reached in the freeze-out volume. In Fig. 1 we demonstrate a schematic phase diagram of nuclear matter which has a liquid-gas phase transition. The shaded area indicates the region of densities and temperatures which can be studied in nuclear multifragmentation processes. We have also shown isentropic trajectories with S/B values of 1, 2, and 4 typical for supernova explosions. One can see, for example, that a nearly adiabatic collapse of the massive stars with typical entropies of 1-2 per baryon passes exactly through the multifragmentation area.

3. IN-MEDIUM MODIFICATION OF NUCLEAR PROPERTIES

Multifragmentation opens a unique possibility to investigate this part of the phase diagram. In particular, the "in-medium" modifications of properties of hot nuclei are very important for astrophysical applications [11,12]. Recently, the symmetry energy of hot nuclei was extracted in ref. [10], and it was demonstrated that it decreased considerably from the values expected for cold isolated nuclei with increasing excitation energy at multifragmentation. In Fig. 2 we show the symmetry energy coefficient γ, which becomes lower with decrease of the impact parameters b, i.e. for the more central collisions. In this case the symmetry energy of hot fragments with mass number A and charge Z is defined as $E^{\rm sym}_{A,Z} = \gamma(A-2Z)^2/A$. The phenomenological parameter γ is approximately 25 MeV for isolated nuclei, in order to describe their binding energies. As one see it decreases down to $\approx$ 15 MeV, and it may be even lower, as shown in the analysis [10].

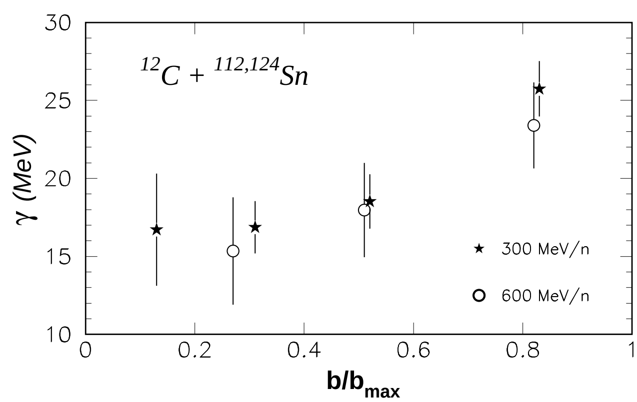

Figure 2. The apparent symmetry energy coefficient γ of hot nuclei, as extracted from multifragmentation of tin isotopes induced by ^{12}C beams with energy 300 and 600 MeV per nucleon, versus relative impact parameter b/b_{max} [10].

As a model which can provide connection between nuclear multifragmentation and astrophysical processes we take the Statistical Multifragmentation Model (SMM), for a review see ref. [2]. As demonstrated by many analyses [3,4,5,6,7,8,9], the model describes experimental data very well. Here a reduction of the symmetry term can be considered as a result of modification of the fragments in hot environment, including mutual interactions between them. Since the SMM can be applied both for finite systems and in the thermodynamical limit for infinite systems, it may be generalized for supernova conditions, where a nuclear statistical equilibration is usually expected. This generalization was performed in refs.[11,12] by including effects of electron, neutrino, and photon interactions in stellar matter.

4. ASTROPHYSICAL IMPORTANCE OF NUCLEAR PROPERTIES

In Fig. 3 we demonstrate the results of SMM calculations both for multifragmentation of Au sources at different excitation energies, and for a stellar matter with density, electron fraction, and temperatures expected during the collapse of massive stars and supernova explosions. One can see that the evolution of mass distributions with excitation energy is qualitatively the same for both the nuclear multifragmentation reactions and the supernova process. The transition with excitation energy (and with temperature) from the 'U-shaped' mass distribution to the exponential distribution, a characteristic feature of the liquid-gas phase transition, is taking place in both cases. However, in the supernova environments much heavier and neutron-rich nuclei can be produced because of screening effect of surrounding electrons.

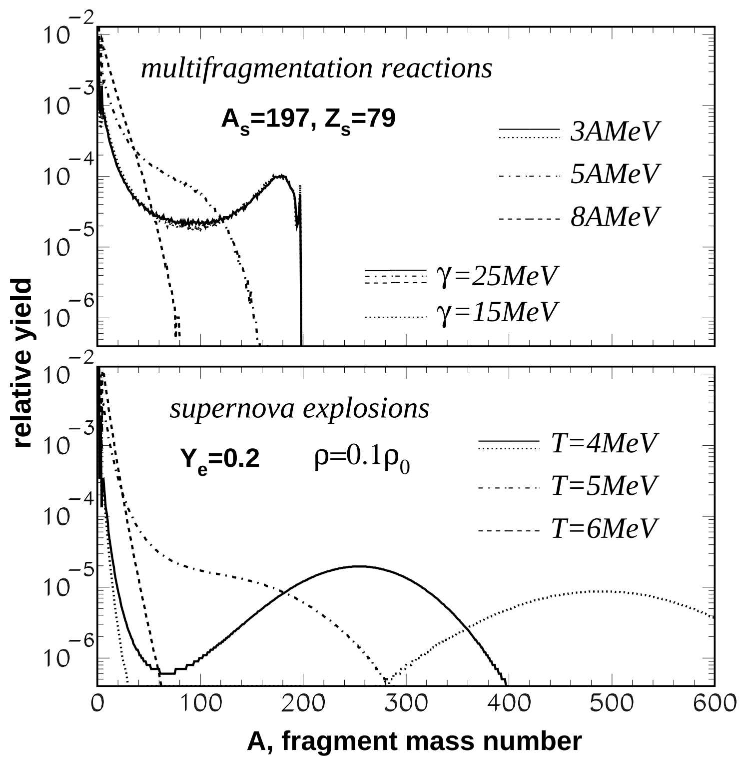

Figure 3. Relative yields of fragments (per one nucleon) in multifragmentation of Au sources (top panel) and in supernova environment at the electron fraction Y_e =0.2 per nucleon and the density of $0.1\rho_0$ (bottom panel). The calculations at excitation energies of 3, 5, and 8 MeV per nucleon (top), and different temperatures T (bottom), are shown by different curves. Effects of the reduced symmetry energy coefficients γ are also demonstrated (top and bottom).

In Fig. 3 we have also shown how important is the information about the symmetry energy of hot nuclei extracted from the experiment. One can see from mass yields at 3 MeV per nucleon in top panel, changing γ coefficient from 25 to 15 MeV has practically no influence on mean mass distributions of fragments produced in nuclear reactions. As was discussed, in the case of multifragmentation of finite nuclei the isotope distributions become wider at smaller γ [13,14]. However, the γ has a dramatic influence on masses of nuclei produced in supernova environment. It is seen that a lot of superheavy (and exotic) nuclei are produced in this case. Their production will influence dynamics of the collapse and explosion. In the following these hot nuclei should undergo de-excitation, and their decay products can serve as seeds for subsequent $r-$ process. In this respect, studying the multifragmentation reactions in the laboratory is important for understanding how heavy elements were synthesized in the Universe.

Changing the symmetry energy of nuclei is also very important for weak interactions. In Fig. 4 we demonstrate that the electron capture rate in stellar matter depends essentially on its value. The calculations of this rate R_e (per nucleon and per second) was carried out with the method suggested in ref. [15], which is based on an independent particle model and dominance of Gamow-Teller transitions. One can see that at relatively high densities $\rho \sim 0.1\rho_0$ the electron capture rate changes only by 20-50%, if we adopt the reduced symmetry energy coefficient. This is because a high electron chemical potential drives the reaction. However, at small densities, when large nuclei still exist (i.e. at low temperatures), the effect of γ could be dramatic, by two-three orders of magnitude. We note, that at these relatively small densities and temperatures the nuclear chemical equilibrium is usually assumed to be established [16]. We believe that hot nuclei interact with each other by neutron exchange in this case. This situation is similar to what we have at higher densities of nuclear matter in multifragmentation reactions. Therefore, the effect of reduction of the symmetry energy observed in multifragmentation may also take place at small densities in supernova environment.

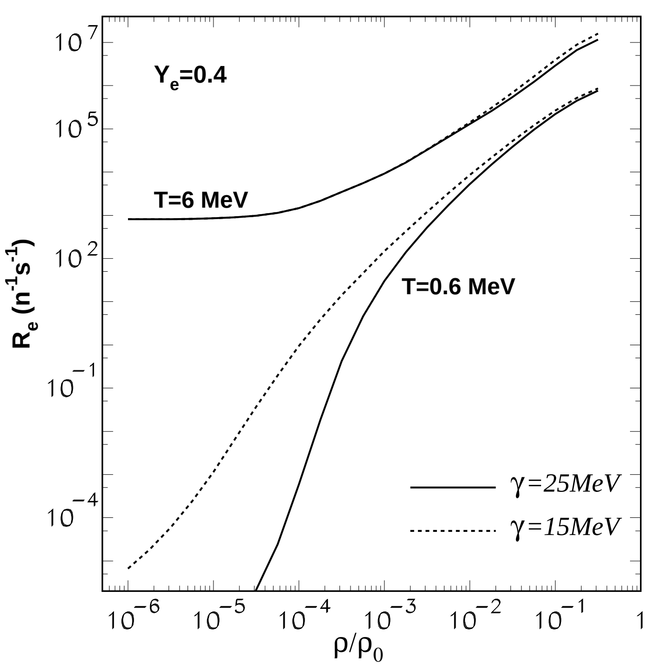

Figure 4. Density dependence of electron-capture rates R_e on hot nuclei in supernova environment at different temperatures T and the electron fraction Y_e=0.4. Solid and dashed lines show results for standard (25 MeV) and reduced (15 MeV) values of the symmetry energy coefficients γ.

5. CONCLUSIONS

We have pointed out that similar physical conditions of nuclear matter are reached in multifragmentation reactions and in explosion of massive stars. Statistical models successfully applied for description of nuclear multifragmentation can be used for astrophysical conditions too. Input parameters of the models (e.g. their symmetry energy, surface energy) can be directly extracted from multifragmentation experiments. Broad variety of nuclei including exotic and neutron-rich ones are produced in stellar matter. Modification of the symmetry energy observed in hot nuclei in dense environment may have strong impact on the weak reaction rates and nucleosynthesis of heavy elements.

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